Kinematics of Gamma-Ray Bursts and Their Relationship to Afterglows

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This article was submitted to
Gamma-Ray Burst and Afterglow Astronomy 2001: A Workshop
Celebrating the First Year of the HETE Mission, Woods Hole,
Massachusetts, November 5-9, 2001

December 17, 2001

U.S. Department of Energy

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Kinematics of Gamma-Ray Bursts and their Relationship to Afterglows

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Abstract. A strong correlation is reported between gamma-ray burst (GRB) pulse lags and afterglow jet-break times for the set of bursts (seven) with known redshifts, luminosities, pulse lags, and jet-break times. This may be a valuable clue toward understanding the connection between the burst and afterglow phases of these events. The relation is roughly linear (i.e. doubling the pulse lag in turn doubles the jet break time) and thus implies a simple relationship between these quantities. We suggest that this correlation is due to variation among bursts of emitter Doppler factor. Specifically, an increased speed or decreased angle of velocity, with respect to the observed line-of-site, of burst ejecta will result in shorter perceived pulse lags in GRBs as well as quicker evolution of the external shock of the afterglow to the time when the jet becomes obvious, i.e. the jet-break time. Thus this observed variation among GRBs may result from a perspective effect due to different observer angles of a morphologically homogeneous populations of GRBs.

Also, a conjecture is made that peak luminosities not only vary inversely with burst timescale, but also are directly proportional to the spectral break energy. If true, this could provide important information for explaining the source of this break.

INTRODUCTION

Only recently, with the discovery of afterglows and in turn, redshifts for a handful of gamma-ray bursts, has there been progress in trend spotting within the seemingly chaotic variety of gamma-ray burst shapes and sizes. Norris et al. [1] discovered an anti-correlation between the isotropic peak gamma-ray luminosity, L_{pk}, of GRBs and the pulse lag, Δt. This lag is the time delay of the arrival of a burst pulse in the BATSE detector low energy channels compared to its arrival in the high energy channels. Similarly Fenimore and Ramirez-Ruiz [2] and also Reichart et al. [3] have shown that a measure of the variability of GRB lightcurves correlates with this peak luminosity. Most recently Frail et al. [4] have shown that the isotropic gamma-ray energy, E_{iso}, is anti-correlated with the jet-break time, τ_j. The jet-break time is when the afterglow lightcurve changes (typically seen as a break) its decay rate, which is thought to be a manifestation of the finite opening angle of the jet.

As demonstrated in Salmonson and Galama [5] these correlations are closely related and are likely manifestations of the same physical effect. As discussed in the next section, we find an unexpectedly tight relationship between spectral lags and jet-break times. Thus we argue that transitivity suggests that L_{pk}, E_{iso}, Δt and τ_j are all interrelated by power-laws. In Salmonson [6, 7] it was argued that the lag-luminosity relationship, L_{pk} vs. Δt, derives from kinematics: the variation in velocity of the relativistic ejecta with respect to the observer. In particular, the Doppler factor, dependent upon the speed and angle of the emitter with respect to the observer, will increase observed luminosity and decrease observed timescales. In Salmonson and Galama [5] we argue that all of these relationships originate from kinematic variations among bursts.

DISCOVERY OF A CORRELATION BETWEEN PULSE LAGS AND JET-BREAK TIMES

In Salmonson and Galama [5] we compare the two burst timescales: the redshift corrected jet-break time, τ_j, and the redshift corrected lags, Δt. We assembled a complete sample of seven bursts for which there are data for Δt, τ_j and redshift z (GRB 971214 has only a lower limit for τ_j, so was not used in fits, but is shown in the figures). Using the CCF31 0.1 lags, $\Delta t_{(CCF31\ 0.1)}$, determined by cross-correlating pulses in BATSE channels 1 & 3 down to 0.1 of the peak luminosity [1], a good fit results:

$$\tau_j = \frac{t_j}{1+z} = 28^{+18}_{-11}\left(\frac{\Delta t_{(CCF31\ 0.1)}}{1\ \text{sec}}\right)^{0.89\pm0.12} \text{days} \quad (1)$$
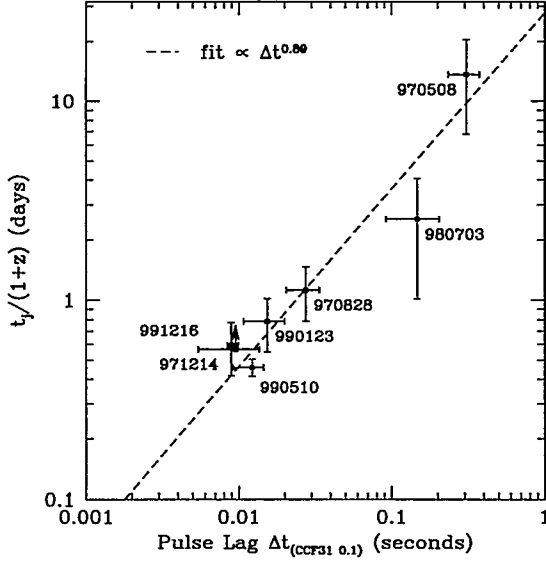
FIGURE 1. Plot from [5] of redshift-corrected burst pulse lags, Δt, observed between BATSE channels 1 and 3, versus observed jet-break times, corrected for redshift, $\tau_j \equiv t_j/(1+z)$. Jet break times t_j are from Frail et al. [4] and pulse lags are from Norris et al. [1]. The fit, given by Eqn. (1), does not include GRB 971214 which only has a lower limit on the jet-break time.

FIGURE 2. Plot from [5] of redshift-corrected burst peak luminosites L_{pk}, versus redshift-corrected observed jet-break times $\tau_j \equiv t_j/(1+z)$. Jet break times t_j are from Frail et al. [4] and luminosities are calculated from Jimenez et al. [12]. Because GRB 971214 only has a lower limit on the jet-break time, it is not included in the fit (given by Eqn. 2).

(shown in Fig. 1) with a reduced chi-squared $\chi_r^2 = 4.7/4$ and a respectable goodness-of-fit $Q = 0.31$ [8].

The existence of such a close relationship between one timescale associated with the GRB itself, and another timescale solely deriving from the afterglow is surprising. The standard GRB paradigm [9] says that the GRB derives from internal shocks in an uneven relativistic wind, while the afterglow comes from a shock sweeping into the ISM, obeying simple self-similar scaling laws and thus not depending on initial conditions imposed by the GRB. In Salmonson and Galama [5] we discuss three possible models to explain the relationship of Eqn. (1).

CONJECTURE: LUMINOSITY IS CORRELATED TO BREAK ENERGY

An enduring mystery in GRBs is the relative constance [10] of the observed break energy, E_0, of GRB spectra, represented by a broken power-law "Band function" [11]. This mystery is doubly troubling in light of the several relationships described earlier in this paper. How can E_0 be constant within a factor of about three while timescales, luminosities, and energies vary over almost two orders of magnitude? Light might be shed on this issue with the observation that there appears to be a corre-
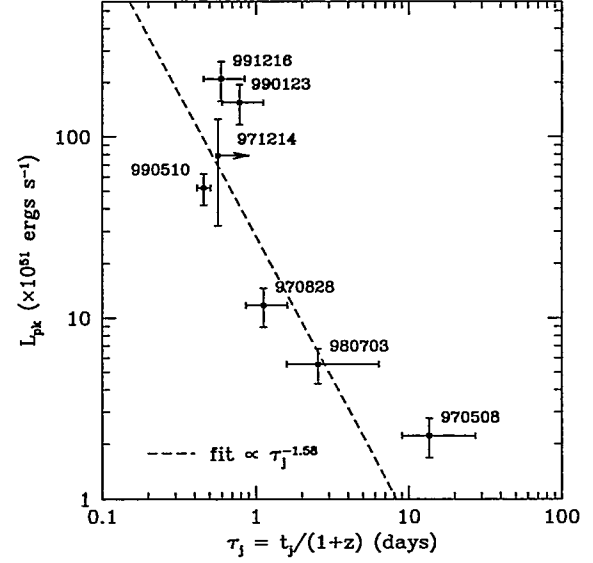
lation between $L_{pk}\tau_j^\beta$ and E_0, where $\beta = 1.58$ is the index for the L_{pk} vs. τ_j power-law relationship (Eqn. 2) found by Salmonson and Galama [5] .

This correlation is demonstrated by comparing the fit L_{pk} vs. τ_j with that of $L_{pk}/E_0/(1+z)$ vs. τ_j. As in Salmonson and Galama [5] we find

$$L_{pk} = 28^{+6}_{-5} \times 10^{51} \left(\frac{\tau_j}{1 \text{ days}}\right)^{-1.58\pm0.23} \text{ergs s}^{-1} \quad (2)$$

(shown in Fig. 2) with $\chi_r^2 = 29/4$ and $Q \sim 10^{-6}$. While the correlation is plainly apparent, the fit is poor, suggesting this relationship is not consistent with a simple power-law.

Now in order to compare with Eqn. (2), I fit $L_{pk}/E_0/(1+z)$ vs. τ_j and find

$$\frac{L_{pk}}{E_0(1+z)} = 4.9 \pm 8 \left(\frac{\tau_j}{1 \text{ days}}\right)^{-1.43\pm0.19}$$
$$\times 10^{49} \text{ergs s}^{-1}\text{keV}^{-1} \quad (3)$$

(shown in Fig. 3) with $\chi_r^2 = 9.9/4$ and $Q = 0.04$. The fit is substantially improved. For the sake of demonstration, the errors for L_{pk} from Eqn. (2) are used in this fit. Realistically one should also factor in the errors in determining E_0.
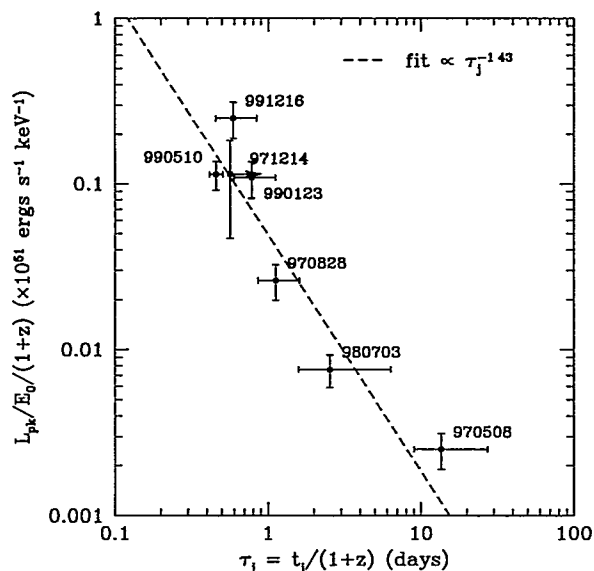
FIGURE 3. Plot of redshift-corrected burst peak luminosites L_{pk} divided by redshift corrected spectral break energies $(1 + z)E_0$, versus redshift-corrected observed jet-break times $\tau_j \equiv t_j/(1+z)$. The fit is given by Eqn. (3). Spectral break energies, E_0, are from Jimenez et al. [12]. See the caption of Fig. 2 for details.

This improvement in the fit of Eqn. (3) over that of Eqn. (2) leads one to hypothesize the existence of an additional dependence on E_0 in the L_{pk} vs. τ_j relationship. Thus I propose

$$L_{pk} \propto E_0^\alpha \tau_j^{-\beta} \qquad (4)$$

where α and β are both roughly unity. This dependence might be indicative of a mechanism for the spectral breaking independent of the physical mechanism behind the relations described previously. One intriguing possibility is that it may indicate a filtering of the gamma-rays that is responsible for the spectral break. As such, the more effective the filter, the lower the energy, E_0, at which the spectrum is broken *and* the more attenuated is the photon flux at all energies. Such a filtering mechanism would require both of these effects to account for the dependence suggested in Eqn. 4. Future observations will be necessary to confirm this conjecture, and future work will elaborate on its physical cause.

This work was performed under the auspices of the U.S. Department of Energy by University of California Lawrence Livermore National Laboratory under contract W-7405-ENG-48.

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